LARGE SCALE DEPLOYMENT OF RENEWABLE ENERGY BY COMBINING WIND FARMS WITH SOLAR THERMAL POWER PLANTS

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ABSTRACT

The installation of megawatt-size wind turbines on 65 to 80 meter towers at Class 4 wind sites in Texas has resulted in the cheapest form of renewable energy ($0.04/kWh). However, wind farm output has a diurnal mismatch to the utility electrical loading. Combining solar thermal power plants with wind farms was shown to result in a good match to the utility loading, and if storage was used then virtually a perfect match could be achieved. The seasonal mismatch for wind farms (i.e. peak load occurs in summer when wind energy is at a minimum) was also improved significantly by combining solar with wind. The peak electrical load during the year is critical to a utility and a wind/solar hybrid was shown to be much better to the utility than a wind alone system for the two regions studied: the Texas Panhandle and Central West Texas.

1. INTRODUCTION

1.1 Background

As the wind industry has evolved from the early 80's, the size of commercially successful utility wind turbines has increased from 40 kW wind turbines on 25 meter towers to 1 to 3 MW wind turbines on 65 to 80 meter towers. The cost of wind generated electricity has decreased from about $0.25/kWh to the current price of about $0.04/kWh (with no state or federal tax incentives – with federal production tax credit the price is ~$0.023/kWh). Technology improvements and economy of scale have helped in decreasing the cost of electricity, but placing the wind turbines on taller towers has resulted in a major reduction in the cost of electricity by a near doubling of the capacity factor in the Great Plains due to the exposure of the wind turbine blades to the nocturnal jet.

Fig. 1 shows a county map of Texas with various cities indicated where wind and solar resource data were used for this paper. In a previous paper (1), an analysis was conducted to determine how well the wind generated electricity from the wind farms in the Texas Panhandle matched the utility loading and ways of increasing the percentage of wind generated electricity in the Texas Panhandle. In that paper, it was discovered that one of the best ways of increasing the percentage of wind generated electricity was to combine it with solar generated electricity. For this paper rather than limiting our scope to just the Texas Panhandle, we also wanted to analyze other parts of Texas – Central West Texas and Far West Texas. The wind data desired in Far West Texas was proprietary, so only solar irradiance data was obtained for Far West Texas, but we expect the results shown for the Texas Panhandle and Central West Texas would be similar for Far West Texas too. The wind and solar resource in other parts of Texas are not as good as that analyzed. The wind resource along the Texas gulf coast is being considered for wind farms, but the wind -- utility load match is much better in that area, so there is not as much need for using solar generated electricity.

Fig. 2 shows evidence of the nocturnal jet in Texas. The average wind speed for each hour for the entire year of 2004 is depicted at three locations in Texas at different heights. The diurnal data at Bushland at the 10 meter height is what everyone is used to for this area (e.g. wind speed increasing in late morning, highest in the afternoon, and then decreasing in the evening). However, for Washburn, TX (exposed to similar winds as Bushland and only 50 km away) at 50 and 75 meter heights the diurnal winds are much different – highest wind speeds are early in the morning and late in the evening and lowest in the afternoon. Average wind speeds for 2004 are shown for Sweetwater, TX (400 km SSE of Bushland in Central West Texas)

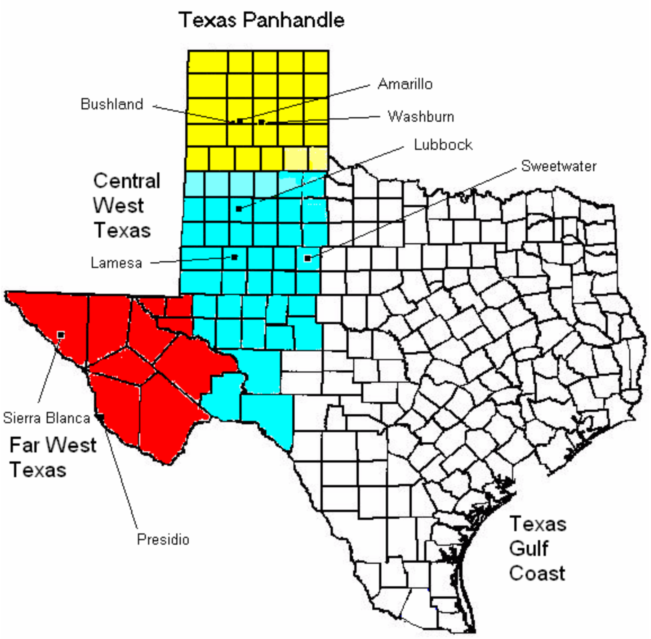

Fig. 1. Locations of wind and solar resource data in Texas.

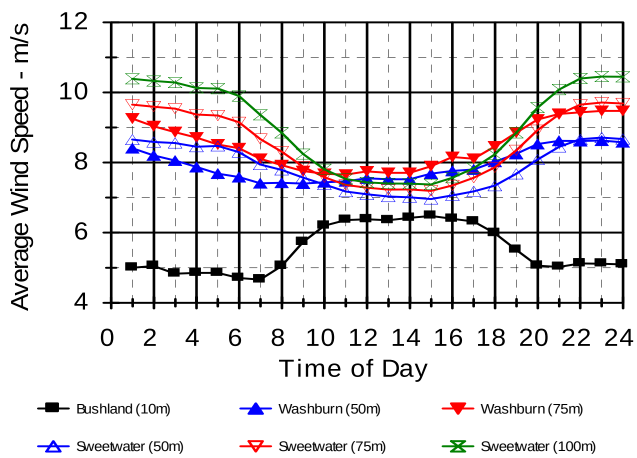

Fig. 2. Nocturnal Jet in Texas (2004).

at heights of 50, 75 and 100 meters. There are some regional variations between the Washburn and Sweetwater sites but the trends are the same (highest wind speeds in the early morning and late night, and lowest wind speeds in the afternoon). A "nocturnal jet" extends over much of the central part of the U.S. including western Minnesota, Nebraska, Dakotas, western Kansas, eastern Colorado, western Oklahoma, western Texas, and eastern New Mexico where the wind speeds are highest at night above some height (that height is 40 meters in the Texas Panhandle). Due to the cubic relationship of wind speed to power (see equation 1) the capacity factors are doubled by increasing the height of the wind turbine towers into this nocturnal jet.

$$P_{wind} = \tfrac{1}{2}\, \rho\, V_{wind}^{3}\, S_{ref} \qquad (1)$$

Where,

P_{wind} --Power in the wind (W)
ρ – air density (kg/m^3)
V_{wind} – velocity of wind (m/s)
S_{ref} – swept area of wind turbine blade rotor (m^2)

However, this has resulted in the wind turbine generating much of its power in the early morning when the utility load is lowest. The high wind generated power in the evening is beneficial since the utility electrical load is usually high in the evening. The cause of the drop in the wind energy in the afternoon is due to the heating affect of solar radiation. When the sun rises in the morning this causes the air next to the ground to heat up and rise. This thermal updraft causes the air to mix which results in the wind speed increasing next to the ground and the wind speed decreasing in the nocturnal jet. Then when the sun sets the mixing stops and the reverse occurs. Since the sun is responsible for the utility load-wind generation diurnal mismatch, it makes sense that solar energy can help with the diurnal mismatch of utility load and wind generated electricity.

Fig. 3 shows the estimated average diurnal capacity factor of parabolic trough solar thermal power plants at locations in California and Texas in 2004. Capacity factor is defined as the ratio of the amount of power actually generated by the power plant to the power generated if it operated at its maximum rating all the time (in percent). Parabolic solar thermal power plants were chosen over other types of solar generated electricity (PV, Power Tower, and Dish Stirling) since currently the largest amount of utility supplied solar generated electricity in the world is with parabolic trough. After a hiatus of 13 years some of these plants are being installed in the U.S. and Spain (2). The largest amount of solar thermal generated electricity in the world (354 MW) is in the Mojave Desert near Barstow, CA, so this location is shown in Fig. 3. The locations in Texas are: Bushland (Texas Panhandle), Lamesa (Central West Texas), Presidio and Sierra Blanca (located near the Rio Grande river in Far West Texas). The average annual capacity factors are shown in parenthesis and the data at Sierra Blanca indicates its output would be similar to that of Barstow. The predicted solar thermal power plant capacity factors shown (18 to 28%) are less than what is currently demonstrated at wind farms in Texas (35 to 45%), but since most of the solar generated electricity is during the afternoon, it is much more valuable to the utility since it occurs during the peak utility loading. This fact is important since the current cost of electricity for a parabolic trough solar thermal power plant is over 3 times that of a wind farm in a Class 4 wind site. However, the cost of solar thermal power plant electricity is projected to be near to that of wind farms in ten years (3).

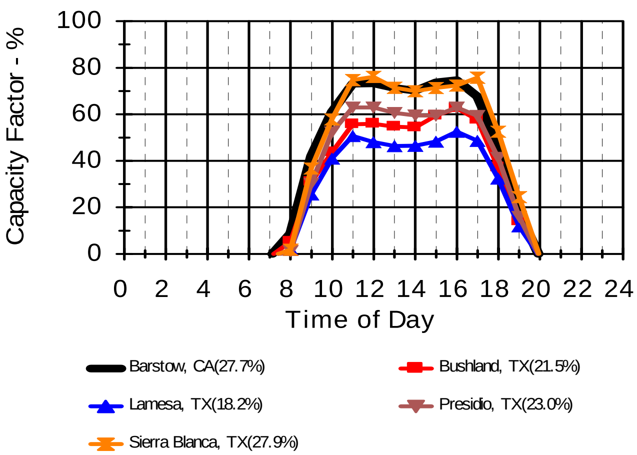

Fig. 3. Estimated Solar Thermal Power Plant Performance at Locations in California and Texas (2004).

1.2 Data Collection and Processing

For this analysis hourly data were used for the electrical loading, wind farm capacity factors, and solar thermal power plant capacity factors. The wind speed height used for the wind farm capacity factor analysis was 75 meters – typical of the hub height used for utility scale wind turbines today. Two cup anemometers were used to collect data at each height at Washburn, TX and Sweetwater, TX. The anemometers were located 3 tower diameters from the center of the communication tower in opposite directions (e.g. SW and NE). This data is in the public domain and can be downloaded off the Alternative Energy Institute website, www.windenergy.org. A computer program was written to calculate the power generated by a 1 MW wind turbine from a published sea level power curve using the highest wind speed measured by the two anemometers (assumed the lower wind speed due to anemometer being in the tower shadow or wake). Capacity factors could vary some with a different wind turbine being used, but the diurnal and monthly trends should be the same. The sea level power was reduced by the factor ($\rho_{actual}/\rho_{Sea\ Level}$) where ρ_{actual} is actual air density and $\rho_{Sea\ Level}$ is sea level air density. The actual air density was calculated based on air temperature, site elevation, and air pressure for Washburn while at Sweetwater it was calculated based on air temperature and site elevation (changes in air pressure should cause at most a 0.5% change in air density). The global solar irradiance data were obtained at two locations in the Texas Panhandle and in Central West Texas to make sure the data were accurate. The global irradiance data collected at Bushland (USDA-ARS lab) was used for the Texas Panhandle while the irradiance data collected from Lamesa (txhighplainset.tamu.edu) was used for Central West Texas – both were pyranometers with typical accuracy of +/-3%. The irradiance data for Presidio and Sierra Blanca (Far West Texas) also used the same pyranometers and can be downloaded off AEI's website. The global irradiance data were converted to direct normal irradiance (DNI) using an Excel spreadsheet (4) that can be downloaded from the National Renewable Energy Lab website (www.nrel.gov). These hourly DNI data were used to calculate the solar thermal power plant performance.

2. RESULTS

2.1 Average Diurnal Results

Fig. 4 shows a comparison of the average daily utility electrical loading compared to the renewable energy capacity factor of a wind farm, solar thermal power plant, and a combination of the two for the Texas Panhandle in 2004. The capacity factor of the wind farm is nearly inversely related to the electrical loading (e.g. almost exact mismatch of utility loading). The solar thermal power plant capacity factor does an excellent job of matching the utility highest loading in the afternoon, but it drops off too rapidly in the evening while the utility load is still high. Another point to note is that the utility load begins picking up in the early morning before the solar thermal power plant begins producing. By combining the wind farm with the solar thermal power plant (assumed 50% wind farm and 50% solar thermal power plant) the renewable energy match is much improved over the wind farm in the afternoon, but worse in the evening. However, this degraded match in the evening could be improved by storing some of the solar thermal heat during the afternoon to be used in the evening. Also, some of the wind generated electricity in the late night and early morning hours can be used to improve the early morning utility match. The wind energy could either be stored in a Compressed Air Energy Storage (CAES) system or used to heat the liquid used in the solar thermal power plant storage system. A report has been released by the Texas State Energy Conservation Office (SECO) on the use of CAES to store wind generated electricity in Texas, Oklahoma, and New Mexico (5). This study found that a 270 MW CAES facility with 10,000 MWh of storage would cost an additional $0.023/kWh. Since a solar thermal power plant storage system would store heat instead of electricity, the system efficiency is estimated to be over 95% (even over a 24 hour period) and the additional cost should be very low. Using the solar thermal storage system to store excess wind generated electricity may be more economical than using CAES.

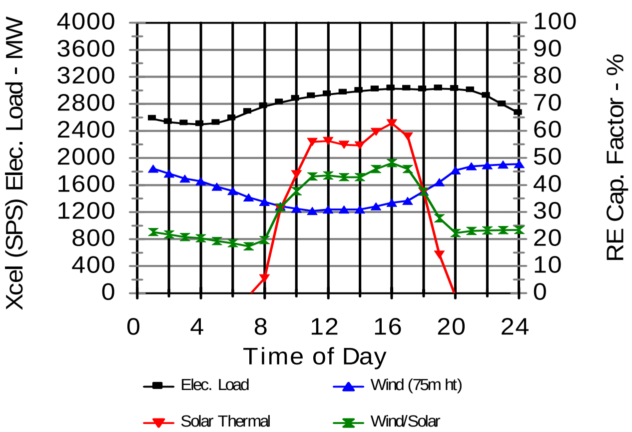

Fig. 4. Average Diurnal Utility Electrical Loading and Renewable Energy Capacity Factors for the Texas Panhandle (2004).

Fig. 5 shows the same comparison as Fig. 4 except it is for Central West Texas. The average peak electrical load occurs at 6 pm for ERCOT (later than for Excel SPS region). The wind farm capacity factor was the same inverse image compared to the utility loading at that for the Panhandle in Fig. 4. During the afternoon the Panhandle data for wind, solar thermal, and wind/solar was higher than that for Central Texas, so there is a better match of renewable energy to utility loading in the Texas Panhandle.

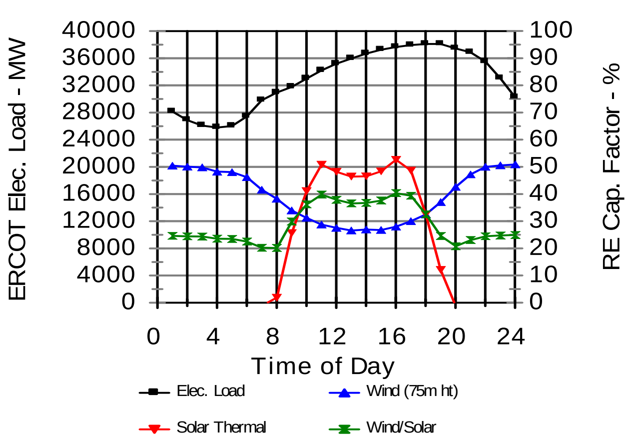

Fig. 5. Average Diurnal Utility Electrical Loading and Renewable Energy Capacity Factors for Central West Texas (2004).

2.2 Average Monthly Results

Fig. 6 shows that for the Texas Panhandle not only is there a mismatch between wind energy and utility electrical loading on a daily basis, there is a seasonal mismatch as well. The utility electrical load peaks in the summer time when the wind farm power production reaches its minimum. According to Fig. 6 the wind farm capacity factor can vary significantly from one year to the next.

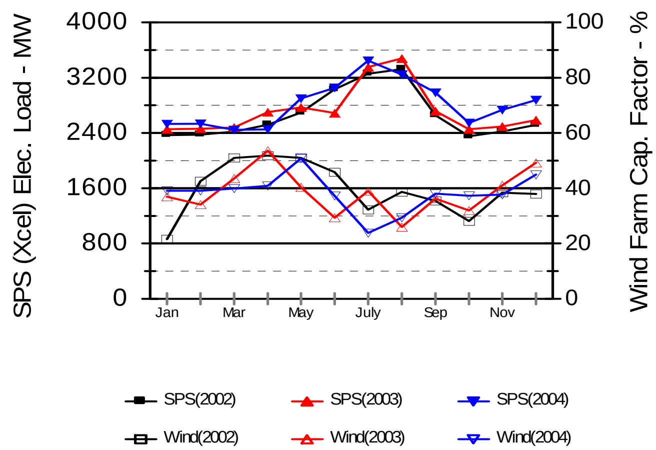

Fig. 6. Average Monthly Utility Electrical Loading and Wind Farm Capacity Factors for the Texas Panhandle.

Fig. 7 shows that for the Texas Panhandle the monthly variation of the utility electrical load is much better approximated by solar thermal energy production than for wind energy production.

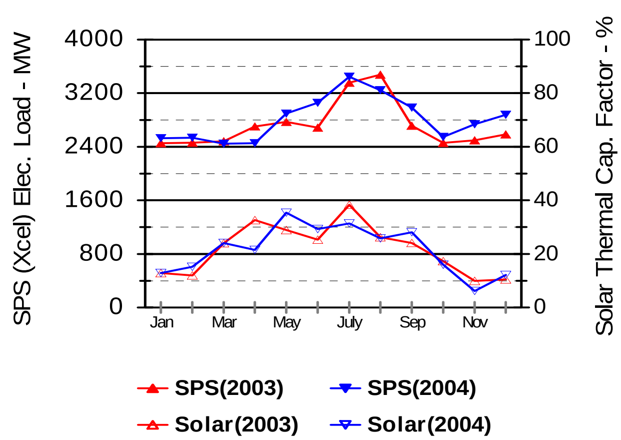

Fig. 7. Average Monthly Utility Electrical Loading and Solar Thermal Power Plant Capacity Factors for the Texas Panhandle.

Fig. 8 and 9 show the effect of combining wind farms with solar thermal power plants for the Texas Panhandle and Central West Texas. Since comparing the data can be confusing, second order polynomials were fit through the data. For both cases there is an obvious improvement in the wind farm seasonal match to the utility electrical loading by adding solar thermal power plants to the renewable energy mix.

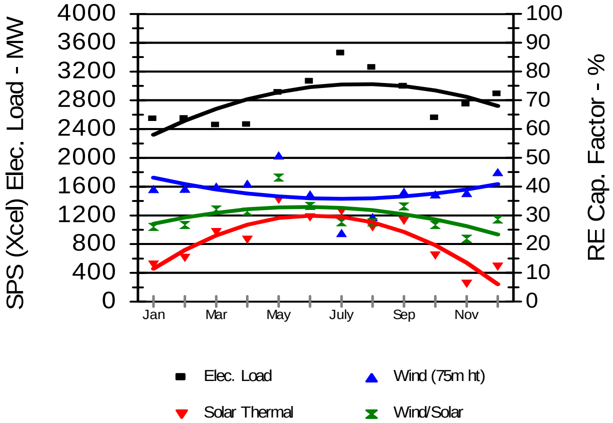

Fig. 8. Average Monthly Utility Electrical Loading and Renewable Energy Capacity Factors for the Texas Panhandle (2004).

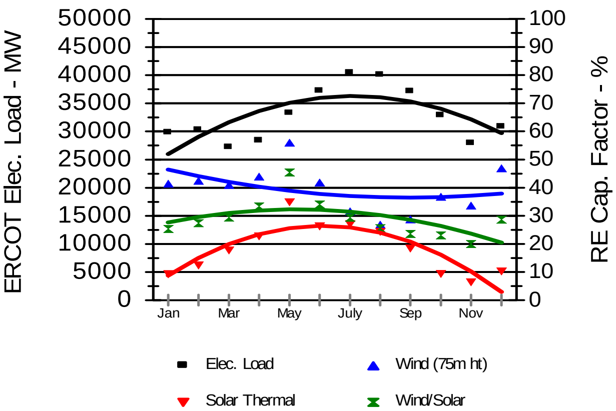

Fig. 9. Average Monthly Utility Electrical Loading and Solar Thermal Power Plant Capacity Factors for Central West Texas (2004).

2.3 <u>Peak Utility Load and Renewable Energy Generation</u>

One of the most important issues for electric utilities is how to either decrease their peak load or increase the amount of generation on the day the utility electrical load peaks. For 2004 the peak utility load day occurred at 4 pm on Aug. 4th in the Texas Panhandle (Fig. 10). Since the peak normally occurs on a hot day then the solar thermal power plant should perform well on that day and Aug. 4th demonstrates this. The solar thermal power plant would have averaged 90% from 9 am to 6 pm. In fact, if the solar thermal power plant operated at 80% and stored 20% of the energy then there would not have been a drop in solar thermal generated power at noon and 3 p.m. The fact that the wind speed increased in the middle of the afternoon during the peak load is more of a fluke than an expected occurrence.

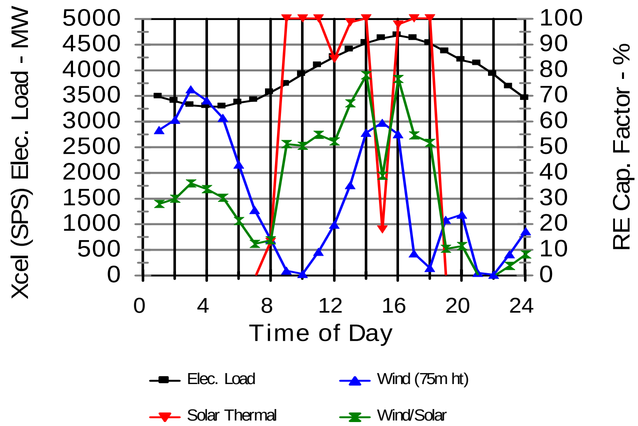

Fig. 10. Peak Diurnal Utility Electrical Loading and Renewable Energy Capacity Factors for the Texas Panhandle (Aug. 4, 2004).

Fig. 11 shows the peak load day for ERCOT and how well renewable energies (wind and solar thermal) in Central West Texas would have performed. While the solar thermal power plant didn't do as well as in the Texas Panhandle, the average solar thermal capacity factor from 9 am to 6 pm was above 75%. However, it is obvious from this graph that the wind generated electricity helped a great deal in the evening when the utility load was still high. From this graph it appears the combination of wind and solar is the best choice.

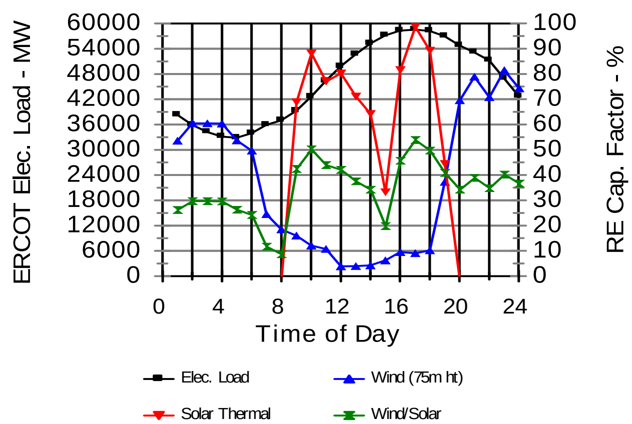

Fig. 11. Peak Diurnal Utility Electrical Loading and Renewable Energy Capacity Factors for Central West Texas (Aug. 3, 2004).

From viewing both Fig. 10 and 11, it is obvious that adding solar thermal power plants in Texas will help meet the utility's peak electrical load during the day, but wind will likely also help the electrical load in the evening when the electrical load will still be high.

3. CONCLUSIONS

For Texas, combining wind farms with solar thermal power plants will result in matching the utility load better than with wind or solar alone. Although the solar thermal power plant will usually perform better during the afternoon than the wind farm (utility load usually peaks in the afternoon in Texas), the wind farm will perform better in the evening when the utility load will still be high. Combining solar thermal power plants with wind farms will also improve the seasonal match of utility load compared to just using wind farms. In Texas, the day the utility peak load occurs is always on a hot day, and solar thermal power generation will always be high on that day while most likely the wind farm during the afternoon peak will either be operating at a low capacity or not at all during the hours of peak loading. Although combining solar thermal power plants with wind farms in Texas will lower the overall capacity factor during the year (as compared to using wind by itself), the electricity will be much more valuable to the utility since it will be generated more often when the utility most needs it (e.g. during peak electrical loads). Since the wind and solar energy will be delivered at different times of the day, then the transmission lines will be utilized more efficiently than by either wind or solar alone. By combining wind with solar the percentage of renewable energy in a Texas utility's total generation should be increased since the utility load – renewable energy generated match will be improved and the overall price of electricity should still be low compared to fossil or nuclear energy and their associated externality costs.

4. FUTURE WORK

Using a CAES system with a wind farm to store the excess wind generated electricity during low utility load periods (late night and early morning), and using a well insulated tank to store the excess heat from the solar thermal power plant during the day should allow the generation of renewable energy to follow the utility loading very well during most days of the year. Instead of using CAES, another possibility is to use the excess wind generated electricity in the late night and early morning hours to power heaters to heat up the liquid being used in the solar thermal power plant storage system since this system is predicted to be more efficient and economical.

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